2012

Characterization of turbidity in Florida's Lake Okeechobee and Caloosahatchee and St. Lucie Estuaries using MODIS-Aqua measurements

Menghua Wang
NOAA National Environmental Satellite, Data, and Information Service, Menghua.Wang@noaa.gov

Carl J. Nim
NOAA National Environmental Satellite, Data, and Information Service

SeungHyun Son
Colorado State University - Fort Collins

Wei Shi
Colorado State University - Fort Collins

Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Characterization of turbidity in Florida's Lake Okeechobee and Caloosahatchee and St. Lucie Estuaries using MODIS-Aqua measurements

Menghua Wang [a,*], *Carl J. Nim* [a,1], *SeungHyun Son* [a,b], *Wei Shi* [a,b]

[a] *NOAA National Environmental Satellite, Data, and Information Service, Center for Satellite Applications and Research, E/RA3, 5830 University Research Ct., College Park, MD 20740, USA*
[b] *CIRA at Colorado State University, Fort Collins, CO, USA*

ARTICLE INFO

Article history:
Received 28 October 2011
Received in revised form
2 June 2012
Accepted 12 July 2012
Available online 21 July 2012

Keywords:
Remote sensing
Water turbidity
Lake Okeechobee
Water quality monitoring

ABSTRACT

This paper describes the use of ocean color remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite to characterize turbidity in Lake Okeechobee and its primary drainage basins, the Caloosahatchee and St. Lucie estuaries from 2002 to 2010. Drainage modification and agricultural development in southern Florida transport sediments and nutrients from watershed agricultural areas to Lake Okeechobee. As a result of development around Lake Okeechobee and the estuaries that are connected to Lake Okeechobee, estuarine conditions have also been adversely impacted, resulting in salinity and nutrient fluctuations. The measurement of water turbidity in lacustrine and estuarine ecosystems allows researchers to understand important factors such as light limitation and the potential release of nutrients from re-suspended sediments. Based on a strong correlation between water turbidity and normalized water-leaving radiance at the near-infrared (NIR) band ($nL_w(869)$), a new satellite water turbidity algorithm has been developed for Lake Okeechobee. This study has shown important applications with satellite-measured $nL_w(869)$ data for water quality monitoring and measurements for turbid inland lakes. MODIS-Aqua-measured water property data are derived using the shortwave infrared (SWIR)-based atmospheric correction algorithm in order to remotely obtain synoptic turbidity data in Lake Okeechobee and normalized water-leaving radiance using the red band ($nL_w(645)$) in the Caloosahatchee and St. Lucie estuaries. We found varied, but distinct seasonal, spatial, and event driven turbidity trends in Lake Okeechobee and the Caloosahatchee and St. Lucie estuary regions. Wind waves and hurricanes have the largest influence on turbidity trends in Lake Okeechobee, while tides, currents, wind waves, and hurricanes influence the Caloosahatchee and St. Lucie estuarine areas.

Published by Elsevier Ltd.

* *Corresponding author*. Tel.: +1 301 683 3325.
E-mail address: Menghua.Wang@noaa.gov (M. Wang).
[1] Present address: US Army Corps of Engineers, Pittsburgh, PA, USA.

0043-1354/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.watres.2012.07.024

1. Introduction

The collective ecosystems of southern Florida are valued for their ecosystem services, aesthetic beauty, abundance of recreational activities and contributions to local economies. Lake Okeechobee provides residents and visitors with a source of drinking water, a sport fishing industry, and irrigation water for surrounding agricultural areas. The adjacent Caloosahatchee and St. Lucie estuaries are also well known for the abundance of ecosystem services and recreational opportunities they provide, in addition to the functional role they serve as drainage basins for Lake Okeechobee overflow (Fig. 1). While these ecosystems have provided numerous benefits to human societies, they have also been modified to suit many human needs, such as flood control, irrigation and navigation, etc. In addition, developmental modifications have taken a toll on the organisms occupying these disturbed habitats and natural resource managers are using science to identify harmful trends in order to restore these valued resources, which have been documented since 2005 on a yearly basis in South Florida Environmental Reports (http://www.sfwmd.gov/sfer/).

Located in southern Florida, Lake Okeechobee is the second largest freshwater lake (~1730 km^2) located entirely within the contiguous United States (Fig. 1). Although Lake Okeechobee is large in areal extent, it is relatively shallow with a mean depth of ~2.7 m. The lake can be classified into three regions based on primary producers (Havens, 2003). The littoral zone (water depth ≤~1 m) is located primarily along the shoreline of the western half of the lake and consists of a suite of biologically diverse plant species, which provide excellent habitat for the spawning of fish. The near shore zone (water depth ~1–2 m), also located along the western half of Lake Okeechobee's coast, is comprised of submerged aquatic vegetation (SAV) and wave tolerant emergent plants and contains a substrate of both sand and peat. The pelagic zone (water depth of ~2.5–5 m) is largely devoid of vegetation and has a muddy substrate (James et al., 2008). The climate and rainfall in the area is characteristic of subtropical locations with a dry (November–April) and wet (May–October) season. However, tropical storms and climatic events, such as hurricanes and El Niño/La Niña oscillations, can substantially alter the hydrology and hydrodynamics of the lake.

In response to devastating hurricanes in the early half of the 20th century, the state of Florida and the Army Corps of Engineers enclosed Lake Okeechobee with the Herbert Hoover dike in order to contain hurricane related flooding. The Herbert Hoover dike also stores freshwater from the watershed in Lake Okeechobee during the dry season for municipal and agricultural water supplies. Drainage canals built to divert excess water from Lake Okeechobee during the wet season now drain most excess water through the Caloosahatchee River to the Gulf of Mexico (west) and the St. Lucie Canal to the Atlantic Ocean (east) instead of the historical drainage route through the Everglades (south) (Fig. 1). While some excess water is routed through southern flowing irrigation canals, these canals divert smaller amounts of water to agricultural areas and the Everglades adjacent to Lake Okeechobee when compared to the Caloosahatchee River and St. Lucie Canal, which discharge water into their estuaries (James et al., 2008).

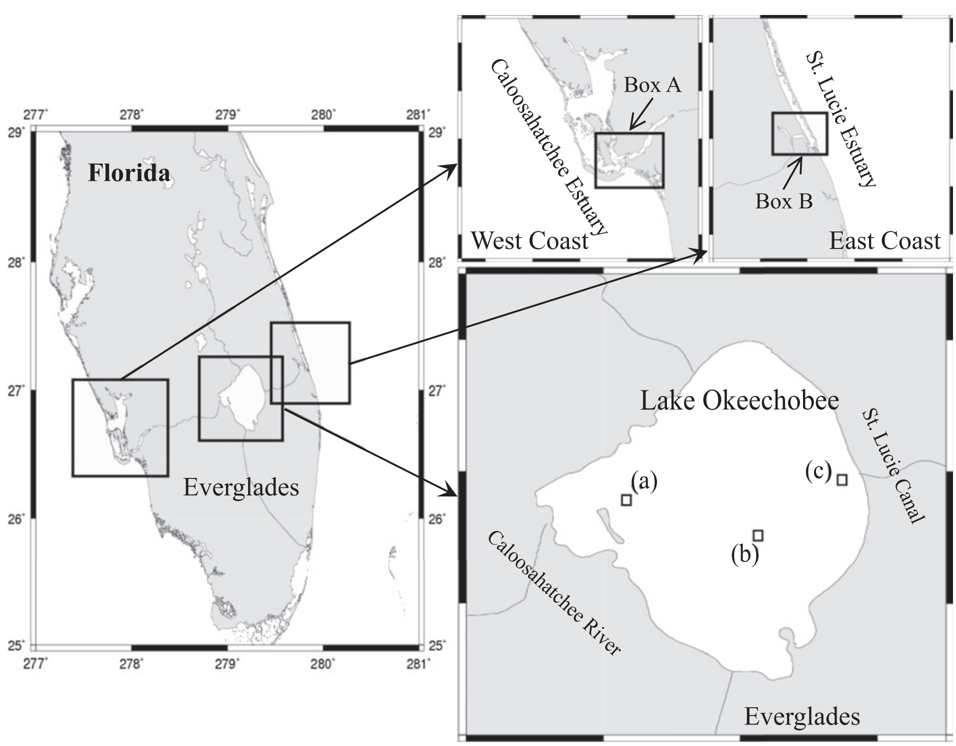

Fig. 1 – Maps of Lake Okeechobee and the Caloosahatchee and St. Lucie estuaries. The study area is marked with three specific locations in Lake Okeechobee (a–c) and Boxes A and B in the Caloosahatchee and St. Lucie estuaries for quantitative studies.

These infrastructural projects have effectively protected human lives and property in areas surrounding Lake Okeechobee, in addition to allowing agriculture to prosper in the region. Unfortunately, they have also transformed Lake Okeechobee into a sink for sediments and fertilizer related nutrient inputs from northern agricultural areas in the Kissimmee Valley, which has made Lake Okeechobee culturally eutrophic (Engstrom et al., 2006; Havens and Walker, 2002; Steinman et al., 1999).

Habitat disturbance is another byproduct of Lake Okeechobee's modification. The vegetated littoral areas of Lake Okeechobee are important for a variety of reasons. Areas with more abundant SAV within Lake Okeechobee have lower amounts of nutrients than areas without SAV, but the mechanism for this is still uncertain (Havens et al., 2007). During hurricanes or periods of high winds, Lake Okeechobee experiences seiches, similar to fluid shaking back and forth inside a bowl. Seiches uproot SAV and emergent macrophytes and re-suspend lake sediments, which obstruct light (Jin et al., 2011), releases nutrients and can impede SAV regrowth for years thereafter (James et al., 2008). Lake stage levels that are too high or too low can also destroy SAV, which results in a decrease of suitable habitat for many juvenile sport fish species. This can potentially affect fish recruitment and population sizes (Havens et al., 2005), as well as Lake Okeechobee's lucrative sport fishing industry (Bell, 1987; Fox et al., 1993; Furse and Fox, 1994; Rogers and Allen, 2008). Multiple fauna utilize the littoral portion of the lake at a variety of life stages (Johnson et al., 2007). Organisms impacted by these changes include zooplankton, macroinvertebrates, amphibians (Havens et al., 1996), and birds (David, 1994) that use the littoral zone for feeding, nesting, or refuge.

The Caloosahatchee River and St. Lucie canal drain into larger estuaries that share their name. Both estuaries were heavily modified and dredged to allow for navigation as a result of natural features (barrier islands, mangroves, and oyster reefs), which deterred easy passage. Estuaries are adapted to a degree of disturbance in relation to natural events, such as hurricanes, which often results in acute changes to the ecosystem. After these events estuaries often rebound quickly (Switzer et al., 2006). With widespread hydrological, residential, and agricultural development in these regions, more chronic stressors have become prevalent, such as persistent salinity disruptions as a result of Lake Okeechobee discharges and increased nutrient concentrations as a result of increased fertilizer use in urban and agricultural areas adjacent to these estuaries (He et al., 2006). These long-term, chronic disturbances are what concern some aquatic biologists (Wan et al., 2006).

The purpose of this study is to provide the long-term remote sensing characterization of turbidity measurements in Lake Okeechobee and the regions surrounding the Caloosahatchee and St. Lucie estuaries from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Salomonson et al., 1989) onboard the Aqua satellite from 2002 to 2010. Remote sensing of coastal and inland waters is valued for its variety in spatial coverage and temporal sampling resolution options (Liu et al., 2003; Wang et al., 2011). MODIS-Aqua measurements of water quality parameters within lacustrine and estuarine ecosystems can provide researchers with broad-scale spatial data and high temporal sampling resolutions at a minimal cost (Chen et al., 2007; Wang et al., 2007). Although MODIS pixels have a nominal spatial resolution of $\sim$1 km for the bands used in this study, remote sensing water quality studies on lakes of Lake Okeechobee's size, specifically China's Lake Taihu (Wang and Shi, 2008; Wang et al., 2011), have been done in the past, in addition to lacustrine comparison studies (James et al., 2009). Remote sensing studies have also been used to understand turbidity characteristics in estuarine ecosystems such as the Chesapeake Bay (Harding et al., 2005; Shi and Wang, 2010a; Son and Wang, 2012), China's east coast (Shi and Wang, 2010b, in press; Shi et al., 2011a, 2011b), and Tampa Bay, Florida (Chen et al., 2007; Hu et al., 2004).

This paper contributes to the substantial amount of water quality data the South Florida Water Management District (SFWMD) can use to make natural resource decisions. While previous studies have investigated the short-term temporal effects of hurricanes on Lake Okeechobee (Daranpob et al., 2009), this study characterizes turbidity trends over a longer period of time (2002–2010), includes the investigation of estuarine ecosystems adjacent to Lake Okeechobee (Caloosahatchee and St. Lucie estuaries), employs a more effective shortwave infrared (SWIR) atmospheric correction algorithm for the areas of interest (Wang, 2007; Wang and Shi, 2007; Wang et al., 2009b), and integrates in situ turbidity data to derive synoptic results of turbidity for Lake Okeechobee.

2. Methods

2.1. *Satellite remote sensing data*

This study analyzed satellite ocean color remote sensing data from 2002 to 2010 in southern Florida. Remote sensing data were obtained from MODIS-Aqua. Global open ocean color products have been routinely produced by NASA using the standard-NIR atmospheric correction algorithm (Gordon, 1997; Gordon and Wang, 1994; IOCCG, 2010; McClain, 2009), which employs the NIR black pixel assumption in open oceans. In coastal and shallow areas, however, the black pixel assumption does not hold (Lavender et al., 2005; Ruddick et al., 2000; Shi and Wang, 2009a; Siegel et al., 2000; Stumpf et al., 2003; Wang and Shi, 2005). In these cases the SWIR-based atmospheric correction method can be used to derive improved ocean (water) color products (Wang, 2007; Wang and Shi, 2007; Wang et al., 2009b). Thus, the NIR-SWIR atmospheric correction algorithm (Wang and Shi, 2007; Wang et al., 2009b) was utilized in this study to process MODIS-Aqua data in order to provide more accurate retrievals of normalized water-leaving radiance spectra $nL_w(\lambda)$, as well as various water quality parameters derived from $nL_w(\lambda)$, such as diffuse attenuation coefficient $K_d(490)$ (Wang et al., 2009a), which is used to quantitatively determine turbidity in coastal areas (Shi and Wang, 2010a; Wang and Shi, 2007) and large inland lakes (Wang et al., 2011). The definition and derivation of $nL_w(\lambda)$ can be found in various references (Gordon, 2005; IOCCG, 2010; Morel and Gentili, 1996; Wang, 2006).

Satellite data used in this study consist of MODIS-Aqua-measured water turbidity in Lake Okeechobee, which is derived from MODIS-measured $nL_w(\lambda)$ using the NIR band ($nL_w(869)$) (details are described below). For highly turbid waters as for Lake Okeechobee, $nL_w(869)$ data are more sensitive to the change of water turbidity as compared to those from $nL_w(\lambda)$ at the red band (e.g., $nL_w(645)$) (Shi and Wang, 2009a, 2010a). This phenomenon (Bowers et al., 1998) is attributed to the dominance of $b_b(\lambda)$ for highly turbid waters in a function of $b_b(\lambda)/(a(\lambda) + b_b(\lambda))$ ($a(\lambda)$ and $b_b(\lambda)$ are total absorption coefficient and backscattering coefficient, respectively), of which $nL_w(\lambda)$ can be expressed as a function (Gordon et al., 1988). For the Caloosahatchee and St. Lucie estuaries, on the other hand, $nL_w(\lambda)$ was obtained using the red band ($nL_w(645)$). In these regions, the NIR $nL_w(869)$ values are quite low and are not sensitive to changes in water turbidity. Satellite-measured $nL_w(645)$ data can be directly related to the water total suspended sediment (TSS) (Miller and McKee, 2004; Shi and Wang, 2009b) and can be used as an indicator for water turbidity. It is noted that the SWIR-based atmospheric correction algorithm (Wang, 2007; Wang and Shi, 2007) for deriving satellite $nL_w(\lambda)$ data (including $nL_w(645)$ and $nL_w(869)$) from MODIS-Aqua have been evaluated and validated in various coastal and inland waters (Wang et al., 2011, 2009b, 2007). Because of substantial submerged aquatic vegetation and emergent macrophytes along the western half of Lake Okeechobee (Fig. 1), it was necessary to mask out these areas in MODIS-Aqua-derived water quality data.

2.2. *In situ data*

A large range of water quality parameters are collected for Lake Okeechobee over an impressive spatial and temporal extent by the SFWMD (www.sfwmd.gov), along with other cooperating state and federal agencies, and are available from the SFWMD database website, DBHYDRO (www.sfwmd.gov/dbhydroplsql). However, depending on the type of in situ measurements to be made, measurements may only be taken biweekly or less, may have temporal gaps, and can be expensive depending on the type of analysis to be performed. These monitoring issues can be mitigated with the use of remote sensing data acquired from MODIS-Aqua, which allows for daily synoptic measurements of turbidity over cloud free areas (Wang and Shi, 2006) of the study region and data are freely available to the public. Remote sensing data alone are not enough, however, and this study has benefited by utilizing in situ turbidity data collected by the SFWMD and obtained from the DBHYDRO website to develop and validate MODIS-Aqua-derived water turbidity data. In situ turbidity data were downloaded for Lake Okeechobee and the Caloosahatchee and St. Lucie estuaries, but only Lake Okeechobee had a substantial amount of match-ups between remote sensing data and in situ data. There are also some in situ data from the Caloosahatchee estuary. Ocean color remote sensing data were then compiled into monthly means of turbidity for 2002–2010. Additional limnology data were collected from 2002 to 2010 to support the remote sensing findings and included parameters such as wind speed, lake stage, and discharge flow for Lake Okeechobee.

2.3. *Development of satellite water turbidity algorithm for Lake Okeechobee*

Using the SWIR-based atmospheric correction algorithm (Wang, 2007), $nL_w(\lambda)$ spectra data (blue to NIR wavelengths) from 2002 to 2010 were derived from MODIS-Aqua measurements for Lake Okeechobee, as well as the Caloosahatchee and St. Lucie estuary regions. We then tested and investigated various approaches relating MODIS-Aqua-derived $nL_w(\lambda)$ data (as well as various $nL_w(\lambda)$ ratios) to the in situ measured water turbidity in the regions. It has been found that, for Lake Okeechobee, in situ water turbidity data measured in Nephelometric Turbidity Units (NTU) are the most strongly correlated to the MODIS-Aqua-derived $nL_w(\lambda)$ at the NIR band ($nL_w(869)$). Fig. 2 provides results of the in situ water turbidity as a function of MODIS-Aqua-measured $nL_w(869)$ for Lake Okeechobee, covering water turbidity values from ~1 to 300 NTU. In fact, water turbidity in Lake Okeechobee can be related to $nL_w(869)$ as

$$Turbidity = 1.26 + 90.547\, nL_w(869) + 75.598\, nL_w(869)^2, \qquad (1)$$

with a correlation coefficient of 0.938 and the root mean squared error (RMSE) of 19.83 NTU (Fig. 2). Note that *Turbidity* and $nL_w(869)$ in Eq. (1) are in units of NTU and $\mathrm{mW\,cm^{-2}\,\mu m^{-1}\,sr^{-1}}$, respectively. Clearly, there are significant NIR radiance $nL_w(869)$ contributions for Lake Okeechobee and therefore it requires the SWIR-based atmospheric correction approach in the satellite data processing for retrieval of water quality data. It should be noted that the turbidity algorithm (Eq. (1)), which is based on satellite and in situ measurements, has been developed specifically for Lake Okeechobee.

MODIS-Aqua-derived water turbidity data from Eq. (1) for Lake Okeechobee can then be compared with in situ turbidity measurements for verification. For the matchup comparison, MODIS-Aqua-derived turbidity data were extracted from a 5 × 5 box centered at the location of the in situ measurements using the same procedure discussed in Wang et al. (2009b). Fig. 3a provides these verification results. The mean ratio and median ratio of the MODIS-Aqua-derived water

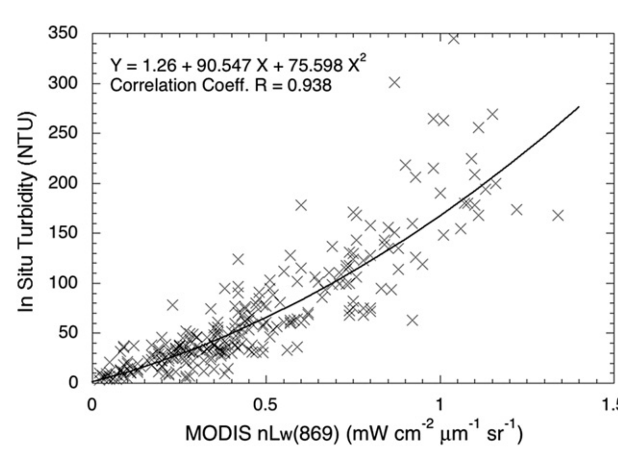

Fig. 2 – In situ-measured water turbidity (NTU) as a function of MODIS-Aqua-derived normalized water-leaving radiance at the wavelength of 869 nm ($nL_w(869)$) for Lake Okeechobee.

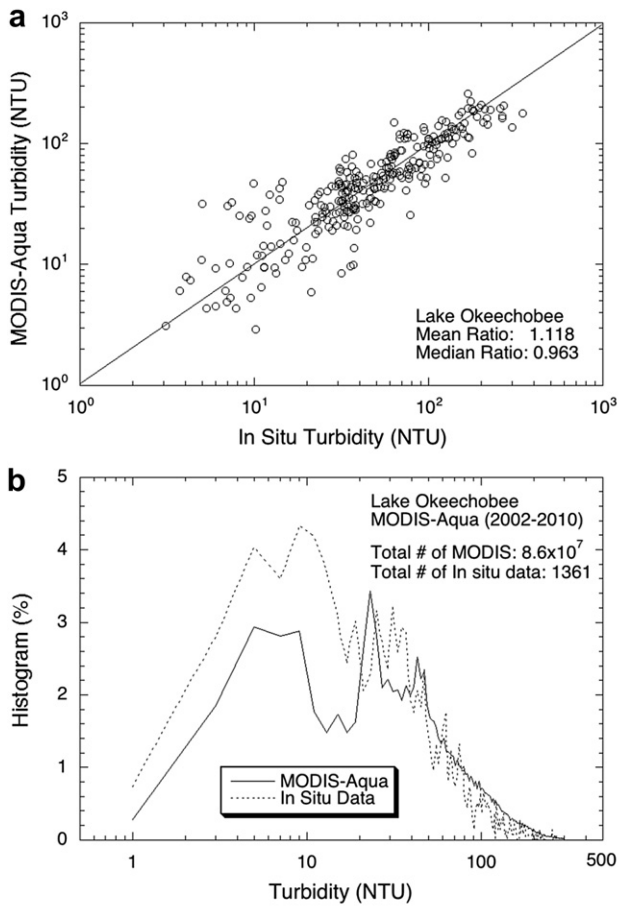

Fig. 3 – MODIS-Aqua-derived water turbidity data (from 2002 to 2010) in Lake Okeechobee compared with in situ measurements for (a) matchup comparisons and (b) histogram results.

turbidity to the in situ-measured data in Lake Okeechobee are 1.118 and 0.963, respectively. Furthermore, Fig. 3b compares histogram results of MODIS-Aqua-derived water turbidity data to in situ measurements. Distribution of the MODIS-derived turbidity data (total number $\sim 8.7 \times 10^7$) appears well matched with in situ measurements (total data number of 1361), although in situ data have more noise in the larger water turbidity values (Fig. 3b). Given the strength of these results, MODIS-Aqua-derived water turbidity data can be used to study and characterize water properties in Lake Okeechobee.

It should be noted that, in order to develop a robust turbidity model (Eq. (1)) for Lake Okeechobee, we have used all available in situ data from 2002 to 2010 and the same data have been used for the algorithm verification. However, before adopting this methodology, we have tested the sub-sample approach for verification and validation. Specifically, we have used the data from 2002 to 2009 to develop a turbidity model (the same formulation as in Eq. (1)) and 1-year data in 2010 to validate the sub-sample-developed turbidity model. The sub-sample (2002–2009 data) developed turbidity formula has a correlation coefficient of 0.927 and the RMSE of 19.72 NTU. MODIS-measured water turbidity data in 2010 over Lake Okeechobee were derived using the sub-sample-developed turbidity formula and compared with the in situ data. In addition, using Eq. (1) for deriving MODIS turbidity data, the same matchup comparison has been carried out for the 2010 data set. These two matchup comparisons (with the sub-sample-developed formula and Eq. (1)) have nearly the same comparison results. For the sub-sample approach, the mean and median ratio values of the MODIS-derived to the in situ-measured water turbidity data (for the 2010 data set) are 1.161 and 1.136, respectively, compared with corresponding values of 1.135 and 1.104 for the approach using Eq. (1). Thus, the MODIS water turbidity formula (Eq. (1)) is valid and used for deriving MODIS water turbidity data for Lake Okeechobee.

3. Results and discussions

The use of remote sensing data from the MODIS-Aqua platform allows for a broader spatial and higher temporal resolution of turbidity patterns within the study areas and is less expensive when compared to in situ measurements due to reduced time and resources needed to collect and analyze turbidity data (Liu et al., 2003). Two of the three distinguishing characteristics of shallow, polymictic lakes, such as Lake Okeechobee, that are outlined by Havens et al. (2001) are (1) frequent mixing of the entire water column and resuspension of unconsolidated sediments and (2) substantial internal loading of nutrients from the sediments to the water column; both of which can be informed by the results presented in this section. Many of our results are in agreement with the findings of other lacustrine and estuarine studies that highlight the role of tides, currents, wind and disturbance events, specifically hurricanes, in the resuspension of sediments throughout these ecosystems (Chen et al., 2010; Havens et al., 2011; James et al., 2008).

3.1. *Results from Lake Okeechobee*

3.1.1. *Seasonal characterization of turbidity in Lake Okeechobee*

The characterization of monthly mean water turbidity levels from 2002 to 2010 in Lake Okeechobee (Fig. 4) allows for the examination of seasonal variation in turbidity within Lake Okeechobee. Turbidity is highest in winter (December–February), moderate in spring and fall seasons (March–May and September–November), and lowest in summer (June–August). The seasonal variation of turbidity in Lake Okeechobee is likely the result of seasonal wind variation on Lake Okeechobee as winds strongly influence sediments in shallow lakes with large fetches (Havens et al., 2007). A lake's susceptibility to resuspension of sediments as a result of wind-driven waves can be determined with the use of an index (Bachman et al., 2000) wherein lakes situated below a dynamic ratio of 0.8 are more likely to exhibit sediment resuspension. This index was calculated in a study by Havens et al. (2007) for Lake Okeechobee and other lakes throughout the world. Lake Okeechobee fell well below the dynamic ratio of 0.8; meaning resuspension in the lake is largely driven by winds. According to the same study, winds on the lake are strongest in the winter when persistently high-speed winds

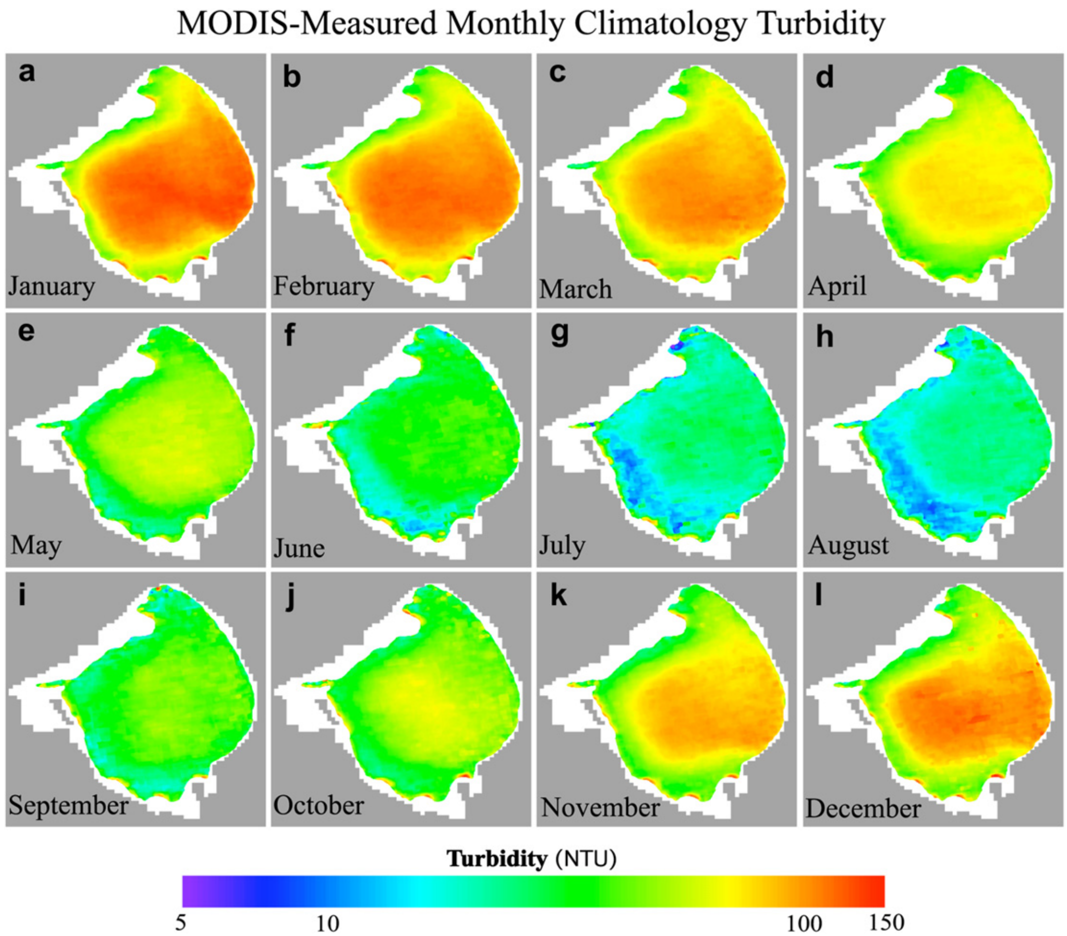

Fig. 4 – MODIS-Aqua-measured (from 2002 to 2010) climatology monthly turbidity images for Lake Okeechobee for months of January to December as in panels of (a)–(l).

can create waves for days. This is evident in the MODIS-Aqua monthly climatology turbidity measurements where values are highest in the winter months of December–February. In the summer, wind speeds are comparably slower and exhibit varying diurnal wind speeds that are highest in the afternoon and evening, due to convectional thunderstorms and sea breezes from the Atlantic Ocean, respectively. MODIS-Aqua monthly climatology measurements of turbidity also illustrate this with the lowest values in the summer months of June through August. The seasonal water turbidity characterization in Lake Okeechobee from MODIS-Aqua measurements is consistent with a previous study using in situ data (Chang et al., 2009). In addition, these data reinforce findings from studies by James et al. (2008, 2009), in which they found a correlation between winds and suspended sediments within Lake Okeechobee.

3.1.2. *Spatial characterization of turbidity in Lake Okeechobee*

MODIS-Aqua measurements of the spatial distribution of turbidity in Lake Okeechobee are characterized by a core and periphery pattern throughout most of the year with the exception of the months in summer where turbidity levels are relatively homogenous (Fig. 4). A number of limnology studies also recognize this trend and attribute it to the varied substrate and aquatic vegetation distribution in Lake Okeechobee. Specifically, Lake Okeechobee has a muddy substrate in the center of the lake, while most of the periphery contains a sandy, vegetated littoral, and near-shore area. As a result of the different substrate and near-shore vegetation, turbidity is generally higher near the muddy core of the lake and lower near the sandy periphery (Havens, 1995, 2003; Phlips et al., 1993). This core-periphery dichotomy can be seen in the MODIS-Aqua-derived monthly climatology of water turbidity (Fig. 4). Another interesting distinction among spatial turbidity patterns can be made within the near shore region of Lake Okeechobee. Turbidity levels for the near shore areas of Lake Okeechobee are lower along the western shore of the lake (which contains more SAV) and higher along the eastern shore of Lake Okeechobee (which contains less SAV), which is also consistent with previous studies (Havens, 2003).

3.1.3. *Hurricane effects on turbidity in Lake Okeechobee*

A number of studies have examined the effects of hurricanes on Lake Okeechobee. An especially active period was from 2004 to 2005. As a result of these events, due to persistently high wind speeds that promoted mixing and disturbed lake sediments, turbidity in the lake doubled in some cases (Fig. 5).

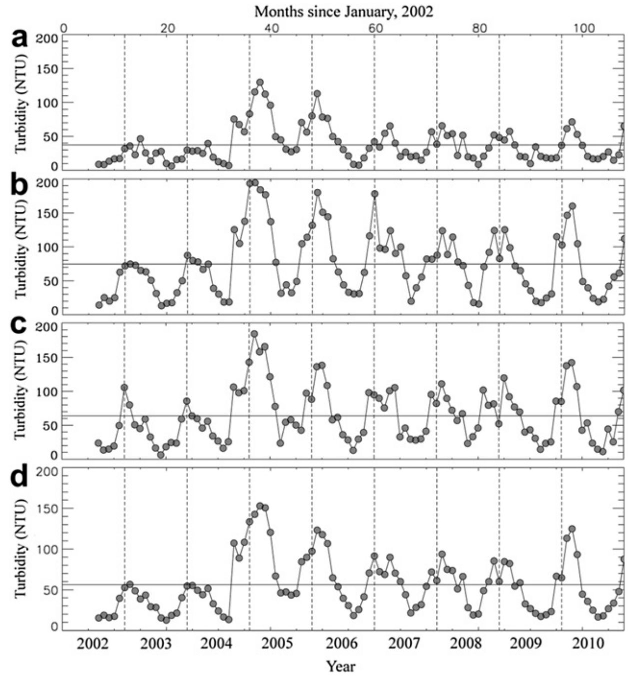

Fig. 5 – Time series of MODIS-Aqua-derived mean monthly water turbidity in Lake Okeechobee from locations of (marked in Fig. 1) (a) western part, (b) central part, (c) eastern part, and (d) average of the entire lake.

The unconsolidated sediments released by extensive wind wave mixing resulted in significantly higher total suspended sediment (TSS) levels after hurricane Wilma (Abtew and Iricanin, 2008) and influenced turbidity characteristics for years thereafter (Havens et al., 2011; James et al., 2008). For example, when hurricane Wilma passed over Lake Okeechobee on October 24, 2005, mean values of water turbidity illustrated the significant impacts of wind on water properties in the lake. MODIS-Aqua-measured 7-day composite turbidity images were derived before (October 17–23) and after (October 25–31) the hurricane with mean values of 70.16 and 159.77 NTU, respectively. MODIS-Aqua measurements (Fig. 5) of turbidity from 2002 to 2010 in the western (Fig. 5a), central (Fig. 5b), and eastern (Fig. 5c) regions of Lake Okeechobee, as well as the entire lake (Fig. 5d) also support this observation. MODIS-Aqua-measured turbidity values in multiple lake sites for years after 2004 had peak periods of turbidity higher than the mean for all years. The highest increases in turbidity occurred after September and October of 2004 as a result of hurricanes Charley (August 13, 2004), Frances (September 5, 2004), Ivan (September 20, 2004), and Jeanne (September 26, 2004). According to James et al. (2008), hurricane Frances had the largest impact on turbidity because it remained over the area for 4.7 days, creating waves and re-suspending 3–6 cm of the sediment column in the muddy central portion of Lake Okeechobee. The next highest increase in turbidity came as a result of hurricane Wilma on October 24, 2005. In subsequent years peak turbidity during the winter was higher than the mean for all years and higher than peak turbidity levels in 2002 and 2003 (see Fig. 5). This trend is echoed in TSS concentrations presented in a study by James et al. (2008). It is noted that numbers of data used for monthly water turbidity computations range from 1–18, 3–20, 1–16, and 7–25 for Fig. 5a, b, c, and d, respectively.

3.2. *MODIS-Aqua-derived* nL_w*(645) in the Caloosahatchee and St. Lucie estuaries*

Turbidity is an important parameter to measure in estuaries. High values of turbidity can shade out SAV like sea grass, disturb valued organisms such as oysters by carrying chemicals or pollutants, and indicate areas of coastal erosion or source deposition (Chen et al., 2007; Shi and Wang, 2009b). MODIS-Aqua-measured normalized water-leaving radiance at the wavelength of 645 nm ($nL_w(645)$) can be used as a proxy to determine TSS concentration at the surface layer of coastal waters (Miller and McKee, 2004). Fig. 6 provides results of in situ water turbidity (NTU) as a function of MODIS-Aqua-derived $nL_w(645)$ for the Caloosahatchee estuary region (Fig. 1). In Fig. 6, a best fit line is also shown, i.e., *Turbidity* (NTU) $= 5.479[nL_w(645)]^{0.7047}$, with a correlation coefficient of 0.6415. However, because there are no in situ turbidity data available in the St. Lucie estuary region, we simply use MODIS-Aqua-measured $nL_w(645)$ data as a water turbidity index for characterizing water properties in the Caloosahatchee and St. Lucie estuaries. Using the SWIR-based atmospheric correction algorithm for turbid waters, monthly climatology images of $nL_w(645)$ were derived for the offshore waters in the Caloosahatchee and St. Lucie estuaries. The SWIR-derived $nL_w(645)$ data have been used and validated in a number of studies in similar environmental settings, specifically estuaries and inland lakes, for understanding of turbidity patterns in coastal waters (Shi and Wang, 2009b, 2010b; Wang et al., 2011).

3.2.1. *Seasonal characterization of* nL_w*(645) in the Caloosahatchee and St. Lucie estuaries*

The highest $nL_w(645)$ measurements for the Gulf of Mexico adjacent to the Caloosahatchee estuary and Charlotte Harbor are in winter months (December–February) with moderate levels in March and April (Fig. 7). Measurements of $nL_w(645)$ are lowest in the region for the months of May–November.

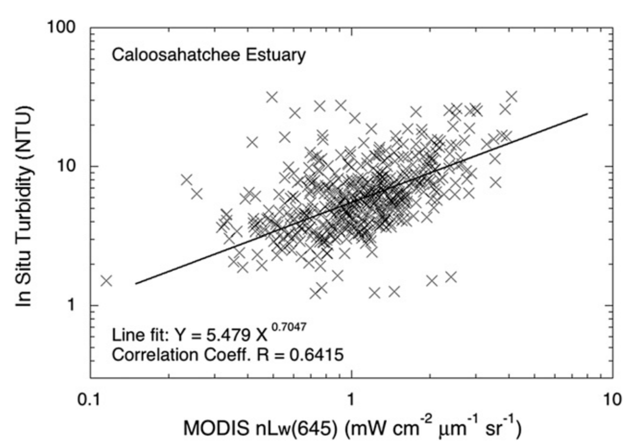

Fig. 6 – In situ-measured water turbidity (NTU) as a function of MODIS-Aqua-derived normalized water-leaving radiance at the wavelength of 645 nm (*$nL_w(645)$*) for the Caloosahatchee estuary.

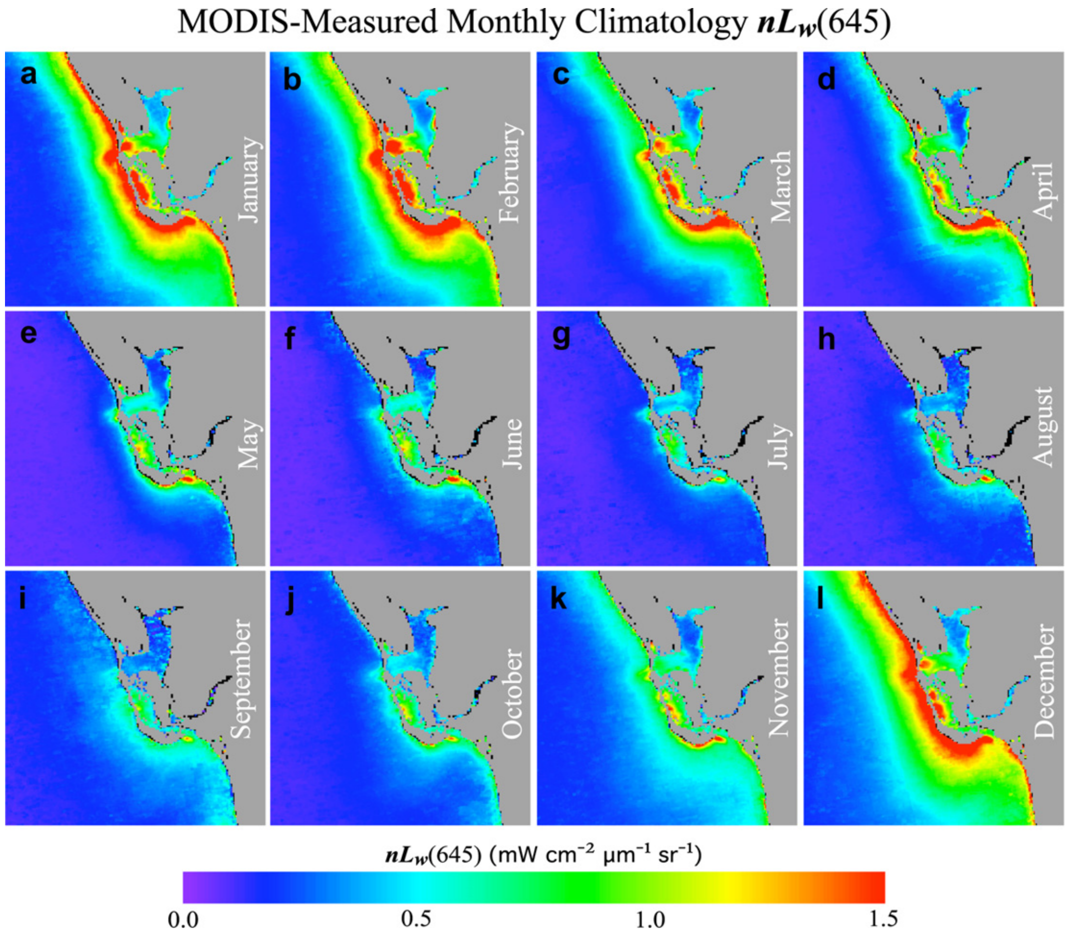

Fig. 7 – MODIS-Aqua-measured (from 2002 to 2010) climatology monthly nL_w(645) images for the Caloosahatchee estuary for months of January to December as in panels of (a)–(l).

These nL_w(645) trends are in agreement with previous studies, which have suggested that wind waves, along with currents, as a result of winter and tropical storms are one of the primary mechanisms for sediment resuspension through bottom wave orbital motions in nearby Tampa Bay (Chen et al., 2007, 2010). Although thunderstorms may be thought of as disruptive, they are typically not as influential as winter or tropical storms given their transient characteristics and limited influence (Schoellhamer, 1995; Shi et al., 2006). Measurements of nL_w(645) for the Atlantic Ocean adjacent to the St. Lucie estuary (Fig. 8) are substantially lower than those in the Gulf of Mexico. Measurements of nL_w(645) are the highest from the months of November through March with moderate levels in April, May, September, and October, and lowest from the months of June through August. Mechanisms for seasonal turbidity trends in the Caloosahatchee and St. Lucie Estuary drainage areas appear to be the result of a combination of wind waves, currents and tides, which will be discussed in more detail later.

3.2.2. *Spatial characterization of* nL_w*(645) in the Caloosahatchee and St. Lucie estuaries*

Within the Caloosahatchee estuary region there is a spatial distinction between the measurements of nL_w(645) along the Florida shelf and inland waters. During periods of high seasonal turbidity (December–February) areas along the Florida shelf have the highest measurements of nL_w(645) (Fig. 7a, b, and l). Inland waterways have comparatively lower measurements of nL_w(645) throughout their water bodies, where data are available. During months of moderate measurements of nL_w(645), March and April (Fig. 7c and d), ocean regions along the Florida shelf exhibit high measurements of nL_w(645) but at a smaller spatial extent. However, during periods of low measurements of nL_w(645) (May–November) only some regions exhibit high measurements of nL_w(645) at very small spatial extents (Fig. 7e–k). The contrast in measurements of nL_w(645) between inland waters and Florida Shelf waters has been observed by Doering and Chamberlain (1998, 1999), who found that TSS levels increased along a gradient from the inlet of the Caloosahatchee estuary to the outlet, indicating waves and currents largely influence turbidity near the mouth of the estuary. Just north of this study site, in Tampa Bay, Chen et al. (2007, 2010) found that turbidity within Tampa Bay was largely influenced by tides, while turbidity at the mouth of Tampa Bay and along the Florida shelf adjacent to the study site was driven by currents and wind waves. Similar mechanisms appear to be driving turbidity in the Caloosahatchee region.

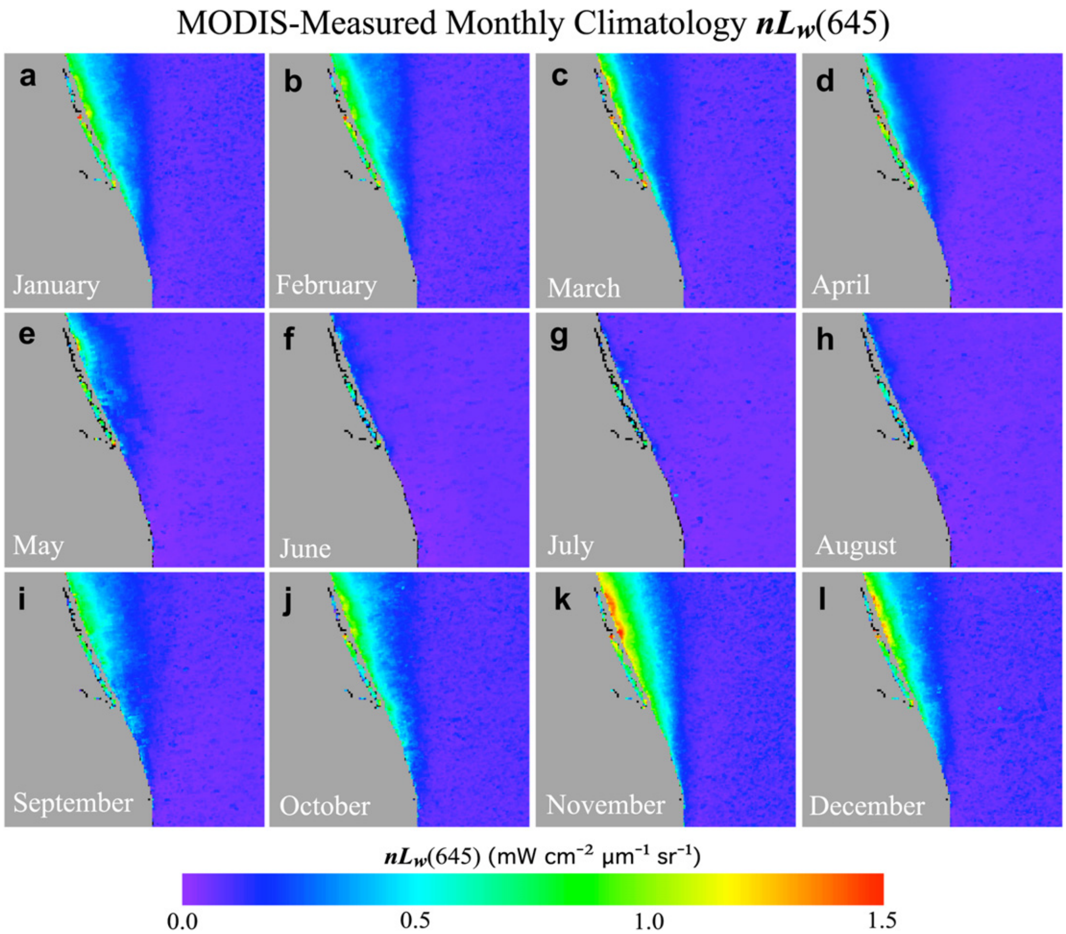

Fig. 8 – MODIS-Aqua-measured (from 2002 to 2010) climatology monthly nL_w(645) images for the St. Lucie estuary for months of January to December as in panels of (a)–(l).

While a clear characterization of nL_w(645) measurements in the Caloosahatchee region may be possible, trends in the St. Lucie region are more subdued (Fig. 8). Potential reasons for this are that the St. Lucie estuary is much smaller (~24 km^2) than the Caloosahatchee estuary (~82 km^2) (Rudnick et al., 2008), it discharges into the Indian River Lagoon and Atlantic Ocean and has a steeper depth gradient from shore to sea than the Caloosahatchee region. As a result of these combined attributes, discerning the spatial characteristics for measurements of nL_w(645) with MODIS-Aqua in the St. Lucie estuary region is difficult. Other complicating factors are the strength of the Gulf Stream current and the steep depth gradient from shore to sea, which appears to dissipate discharge from the St. Lucie estuary and send it north, or facilitate settlement respectively. Despite these complications, some spatial trends can be identified. Measurements of nL_w(645) near the mouth of the St. Lucie estuary are moderate from November–March and low from April–October. While the St. Lucie estuary is not large enough to show up with MODIS-Aqua data, the Indian River lagoon is. In the central portion of the Indian River lagoon near the Sebastian Inlet some spatial trends can be observed. Measurements of nL_w(645) here are strongest in November, moderate in December and March, and low in January, February, and April. In another study, Qian et al. (2007) examined in situ measurements from 1979 to 2004 of multiple parameters in the same region, turbidity being one of them. Researchers found no clear seasonal trend in all three stations for turbidity. In fact each station differed from the next based on whether there was a seasonal difference and when the seasonal difference took place, specifically the wet or dry season. In the case of the St. Lucie estuary, geographic characteristics such as the narrow north-south alignment of the Indian River lagoon and St. Lucie estuary, along with the strength of the Gulf Stream and steep depth gradient from shore to sea may confound any substantial spatial patterns of nL_w(645) measurements.

3.2.3. *Interannual characterization of* nL_w(645) *in the Caloosahatchee and St. Lucie estuaries*

Clear quantitative distinctions of nL_w(645) can be made when examining the interannual characteristics between the water clarity of the Caloosahatchee estuary and the St. Lucie estuary in Boxes A and B (locations and spatial coverage shown in Fig. 1) from MODIS-Aqua nL_w(645) measurements (Fig. 9). Seasonal variation is evident with higher nL_w(645) (turbidity) levels occurring in the winter and spring and lower levels occurring in the summer. Overall MODIS-Aqua

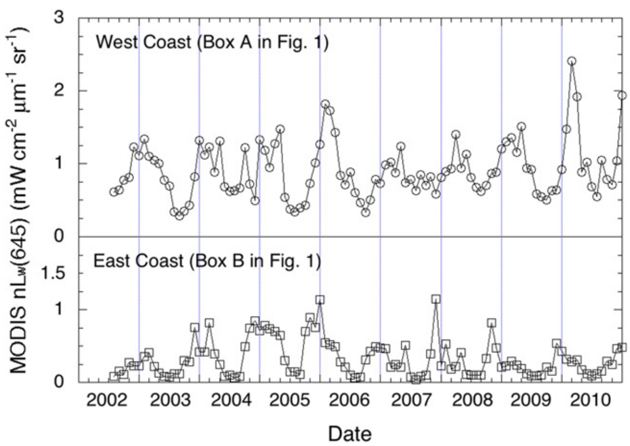

Fig. 9 – Time series of MODIS-Aqua-derived monthly $nL_w(645)$ data from regions of Box A (marked in Fig. 1) in the Caloosahatchee estuary (top panel) and Box B (marked in Fig. 1) in the St. Lucie estuary (bottom panel).

measurements of water turbidity are higher in the Caloosahatchee estuary when compared with the St. Lucie estuary. Peak winter $nL_w(645)$ levels for the St. Lucie estuary do not exceed 1.25 mW cm^{-2} μm^{-1} sr^{-1}, whereas peak winter $nL_w(645)$ levels for the Caloosahatchee estuary range from ∼1.25 to 2.3 mW cm^{-2} μm^{-1} sr^{-1}. Minimum $nL_w(645)$ measurements in the Caloosahatchee estuary are not lower than ∼0.25 mW cm^{-2} μm^{-1} sr^{-1}, whereas the majority of $nL_w(645)$ measurements for the St. Lucie estuary fall below ∼0.5 mW cm^{-2} μm^{-1} sr^{-1}. While persistent seasonal physical forces such as winter winds and tidal currents play a large role in the interannual characteristics exhibited in the MODIS-Aqua measurements of $nL_w(645)$, hurricanes and other disturbance events also figure into water turbidity trends within these estuaries and are discussed next.

3.2.4. *Hurricane effects on turbidity in the Caloosahatchee and St. Lucie estuaries*

Because of the interconnectedness of Lake Okeechobee to the St. Lucie and Caloosahatchee estuaries, precipitation falling within the Lake Okeechobee watershed can affect these estuarine ecosystems in addition to weather events that occur within their own watersheds. Hurricanes affect estuaries in many of the same ways they affect Lake Okeechobee by contributing large amounts of freshwater, which move nutrients and sediments to the estuary. Associated winds and storm surge also disturb sea grass beds (Steward et al., 2006) and nekton communities (Switzer et al., 2006), albeit disruption is generally short-lived. Although seasonal and spatial $nL_w(645)$ measurement patterns are subdued in some regions, disturbance events are not. Half of the spikes in turbidity within the Caloosahatchee and St. Lucie estuarine areas were the result of the 2004 and 2005 hurricanes. Sharp increases in $nL_w(645)$ measurements during the months of the 2004–2005 hurricanes can be seen in Fig. 9. Note that numbers of data used in Fig. 9 for monthly $nL_w(645)$ computations range from 6 to 23 and 5–21 for the west coast (Box A in Fig. 1) and east coast (Box B in Fig. 1), respectively. Although $nL_w(645)$ measurements are larger for the Caloosahatchee estuary site and smaller for the St. Lucie site, noticeable increases in the measurements of $nL_w(645)$ after August 2004 and October 2005 illustrate the substantial effects hurricanes have on the ecosystems of southern Florida. Shortly after these hurricanes, southern Florida experienced a prolonged drought from October of 2006 to August of 2008. During this drought, a period of heavy rains in October of 2007 (Tunberg et al., 2009) potentially stimulated a spike in $nL_w(645)$ measurements for the St. Lucie estuary region. Later, in August of 2008, rainwater from tropical storm Fay facilitated another increase in $nL_w(645)$ measurements. After the hurricanes of 2004 and 2005, $nL_w(645)$ measurement patterns in the Caloosahatchee region were relatively normal with the highest measurements occurring in the months of December–March and the lowest measurements occurring from May through September. The anomaly to this pattern occurred after November of 2009, and can possibly be attributed to the passage of hurricane Ida (November 4th–10th of 2009) in the Gulf of Mexico. These findings are interesting because in some cases these events are not captured by in situ monitoring platforms. With the aid of remote sensing data it is possible to obtain a much higher temporal sampling resolution in addition to being able to interpret events at a broader spatial scale.

4. Conclusion

This paper provides an overview of water turbidity and $nL_w(645)$ measurements and trends in Lake Okeechobee and the regions surrounding the Caloosahatchee and St. Lucie estuaries. In particular, water turbidity in Lake Okeechobee can be reasonably derived using MODIS-Aqua-measured normalized water-leaving radiance at the NIR band ($nL_w(869)$), demonstrating important applications of $nL_w(869)$ for water quality monitoring and measurements for highly turbid inland lakes. This approach can certainly be used for other turbid coastal and inland lake waters for remote sensing of water quality. In conjunction with in situ measurements of turbidity in Lake Okeechobee and the use of the SWIR-based atmospheric correction algorithm, this study provides a perspective of seasonal, spatial, and event related turbidity trends within Lake Okeechobee and $nL_w(645)$ measurements of the Caloosahatchee and St. Lucie estuaries. In this study, turbidity and $nL_w(645)$ measurements from MODIS-Aqua have illustrated their effectiveness in providing accurate, reliable, and synoptic measurements of turbidity in the southern ecosystems of Florida. In some cases MODIS-Aqua measurements were capable of recording events that some in situ monitoring efforts did not obtain. With the availability of additional in situ turbidity data for off-shore areas adjacent to Florida estuaries it would be possible to obtain even more rigorous retrievals of turbidity measurements. The utility of this study lies in its ability to provide researchers and managers with a more comprehensive understanding of turbidity characteristics in the ecosystems they study and manage. With predictions of more hurricanes and extreme weather events as a result of climate change, studies such as this can document local disturbance events and provide insight to how global forces are affecting local ecosystems.

Acknowledgments

This research was supported by NASA and NOAA funding and grants. We would like to thank Trish Burke at the South Florida Water Management District (SFWMD) and Eric Milbrandt at Sanibel-Captiva Conservation Foundation (SCCF) for providing us with water quality data. In situ turbidity data for Lake Okeechobee were obtained from the SFWMD DBHYDRO website. MODIS L1B data were obtained from the NASA Goddard Space Flight Center's MODIS Adaptive Processing System Web site. We thank three anonymous reviewers for their useful comments. The views, opinions, and findings contained in this paper are those of the authors and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

REFERENCES

Abtew, W., Iricanin, N., 2008. Hurricane effects on south Florida water management system: a case study of hurricane Wilma of October 2005. Journal of Spatial Hydrology 8, 1–21.

Bachman, R.W., Hoyer, M.V., Canfield Jr., D.E., 2000. The potential for wave disturbance in shallow Florida lakes. Lake and Reservoir Management 16, 281–291.

Bell, F.W., 1987. The Economic Impact and Valuation of the Recreational and Commercial Fishing Industries of Lake Okeechobee, Florida. Florida Game and Fresh Water Fish Commission, Tallahassee, FL.

Bowers, D.G., Boudjelas, S., Harker, G.E.L., 1998. The distribution of fine suspended sediments in the surface waters of the Irish Sea and its relation to tidal stirring. International Journal of Remote Sensing 19, 2789–2805.

Chang, N.B., Daranpob, A., Yang, Y.J., Jin, K.R., 2009. Comparative data mining analysis for information retrieval of MODIS images: monitoring lake turbidity changes at Lake Okeechobee, Florida. Journal of Applied Remote Sensing 3, 033549. http://dx.doi.org/10.1117/1.3244644.

Chen, Z., Chuanmin, H., Muller-Karger, F., 2007. Monitoring turbidity in Tampa Bay using MODIS/Aqua 250-m imagery. Remote Sensing of Environment 109, 207–220.

Chen, Z., Hu, C., Muller-Karger, F.E., Luther, M.E., 2010. Short-term variability of suspended sediment and phytoplankton in Tampa Bay, Florida: observations from a coastal oceanographic tower and ocean color satellites. Estuarine Coastal and Shelf Science 89, 62–72.

Daranpob, A., Chang, N., Jin, K., Yang, Y.J., 2009. Monitoring the algal bloom event in lake Okeechobee, Florida, under tropical cyclone Fay impacts using MODIS/Terra images. Proceedings of SPIE 7454.

David, P.G., 1994. Wading bird use of lake Okeechobee relative to fluctuating water levels. Wilson Bulletin 106, 719–732.

Doering, P.H., Chamberlain, R.H., 1998. Water quality in the Caloosahatchee Estuary, San Carlos Bay and Pine Island sound. In: Proceedings of the Charlotte Harbor Public Conference and Technical Symposium, pp. 229–240. Charlotte Harbor National Estuary Program Technical Report, Punta Gorda, FL.

Doering, P.H., Chamberlain, R.H., 1999. Water quality and source of freshwater discharge to the Caloosahatchee Estuary, Florida. Journal of the American Water Resources Association 35, 793–806.

Engstrom, D.R., Schottler, S.P., Leavitt, P.R., Havens, K.E., 2006. A reevaluation of the cultural eutrophication of Lake Okeechobee using multiproxy sediment records. Ecological Applications 16, 1194–1206.

Fox, D.D., Gornak, S., McCall, T.D., Brown, D.W., Morris, C.J., 1993. Lake Okeechobee Fisheries Investigations Completion Report. Florida Game and Fresh Water Fish Commission, Tallahassee, FL.

Furse, J.B., Fox, D.D., 1994. Economic fishery valuation of five vegetation communities in Lake Okeechobee, Florida. Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies 48, 575–591.

Gordon, H.R., 1997. Atmospheric correction of ocean color imagery in the Earth observing system era. Journal of Geophysical Research 102, 17081–17106.

Gordon, H.R., 2005. Normalized water-leaving radiance: revisiting the influence of surface roughness. Applied Optics 44, 241–248.

Gordon, H.R., Brown, O.B., Evans, R.H., Brown, J.W., Smith, R.C., Baker, K.S., Clark, D.K., 1988. A semianalytic radiance model of ocean color. Journal of Geophysical Research 93, 10909–10924.

Gordon, H.R., Wang, M., 1994. Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm. Applied Optics 33, 443–452.

Harding Jr., L.W., Magnuson, A., Mallonee, M.E., 2005. SeaWiFS retrievals of chlorophyll in Chesapeake Bay and the mid-Atlantic bight. Estuarine, Coastal and Shelf Science 62, 75–94.

Havens, K.E., 1995. Particulate light attenuation in a large subtropical lake. Canadian Journal of Fisheries and Aquatic Sciences 52, 1803–1811.

Havens, K.E., 2003. Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. Hydrobiologia 493, 173–186.

Havens, K.E., Beaver, J.R., Casamatta, D.A., East, T.L., James, R.T., McCormick, P., Phlips, E.J., Rodusky, A.J., 2011. Hurricane effects on the planktonic food web of a large subtropical lake. Journal of Plankton Research 33, 1081–1094.

Havens, K.E., Bull, L.A., Warren, G.L., Crisman, T.L., Phlips, E.J., Smith, J.P., 1996. Food web structure in a subtropical lake ecosystem. Oikos 75, 20–32.

Havens, K.E., Fox, D., Gornak, S., Hanlon, C., 2005. Aquatic vegetation and largemouth bass population responses to water-level variations in Lake Okeechobee, Florida (USA). Hydrobiologia 539, 225–237.

Havens, K.E., Fukushima, T., Xie, P., Iwakuma, T., James, R.T., Takamura, N., Hanazato, T., Yamamoto, T., 2001. Nutrient dynamics and the eutrophication of shallow lakes Kasumigaura (Japan), Donghu (PR China), and Okeechobee (USA). Environmental Pollution 111, 263–272.

Havens, K.E., Jin, K.R., Iricanin, N., James, R.T., 2007. Phosphorus dynamics at multiple time scales in the pelagic zone of a large shallow lake in Florida, USA. Hydrobiologia 581, 25–42.

Havens, K.E., Walker, W.W., 2002. Development of a total phosphorus concentration goal in the TMDL process for Lake Okeechobee, Florida (USA). Lake and Reservoir Management 18, 227–238.

He, Z.L., Zhang, M., Stofella, P.J., Yang, X.E., 2006. Vertical distribution and water solubility of phosphorus and heavy metals in sediments of the St. Lucie Estuary, South Florida, USA. Environmental Geology 50, 250–260.

Hu, C., Chen, Z., Clayton, T.D., Swarzenski, P., Brock, J.C., Muller-Karger, F.E., 2004. Assessment of estuarine water-quality indicators using MODIS medium-resolution bands: initial results from Tampa Bay, FL. Remote Sensing of Environment 93, 423–441.

IOCCG, 2010. Atmospheric correction for remotely-sensed ocean-colour products. In: Wang, M. (Ed.), Reports of the International Ocean-Colour Coordinating Group. IOCCG, Dartmouth, Canada.

James, R.T., Chimney, M.J., Sharfstein, B., Engstrom, D.R., Schottler, S.P., East, T., Jin, K., 2008. Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). Fundamental and Applied Limnology 172, 273–287.
James, R.T., Havens, K., Zhu, G., Qin, B., 2009. Comparative analysis of nutrients, chlorophyll and transparency in two large shallow lakes (Lake Taihu, P.R. China and Lake Okeechobee, USA). Hydrobiologia 627, 211–231.
Jin, K.R., Chang, N.B., Ji, Z.G., James, R.T., 2011. Hurricanes affect the sediment and environment in lake Okeechobee. Critical Reviews in Environmental Science and Technology 41, 382–394.
Johnson, K.G., Allen, M.S., Havens, K.E., 2007. A review of littoral vegetation, fisheries, and wildlife responses to hydrologic variation at Lake Okeechobee. Wetlands 27, 110–126.
Lavender, S.J., Pinkerton, M.H., Moore, G.F., Aiken, J., Blondeau-Patissier, D., 2005. Modification to the atmospheric correction of SeaWiFS ocean color images over turbid waters. Continental Shelf Research 25, 539–555.
Liu, Y., Islam, M.A., Gao, J., 2003. Quantification of shallow water quality parameters by means of remote sensing. Progress in Physical Geography 27, 24–43.
McClain, C.R., 2009. A decade of satellite ocean color observations. Annual Review of Marine Science 1, 19–42.
Miller, R.L., McKee, B., 2004. Using MODIS terra 250 m imagery to map concentrations of total suspended matter in coastal waters. Remote Sensing of Environment 93, 259–266.
Morel, A., Gentili, G., 1996. Diffuse reflectance of oceanic waters. III. Implication of bidirectionality for the remote-sensing problem. Applied Optics 35, 4850–4862.
Phlips, E.J., Aldridge, F.J., Hansen, P., Zimba, P.V., Ihnat, J., Conroy, M., Ritter, P., 1993. Spatial and temporal variability of trophic state parameters in a shallow subtropical lake (Lake Okeechobee, Florida, USA). Archiv Fur Hydrobiologie 128, 437–458.
Qian, Y., Migliaccio, K.W., Wan, Y., Li, Y.C., Chin, D., 2007. Seasonality of selected surface water constituents in the Indian River Lagoon, Florida. Journal of Environmental Quality 36, 416–425.
Rogers, M.W., Allen, M.S., 2008. Hurricane impacts to Lake Okeechobee: altered hydrology creates difficult management trade offs. Fisheries 33, 11–17.
Ruddick, K.G., Ovidio, F., Rijkeboer, M., 2000. Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. Applied Optics 39, 897–912.
Rudnick, D., Madden, C., Bennett, R., McDonald, A., Kelly, S., Cunniff, K., Alleman, R., Chamberlain, R., Doering, P., Gostel, M., Haunert, D., Hedgepeth, M., Hunt, M., Orlando, B., Qiu, C., Walker, P., 2008. Chapter 12: Management and Restoration of Coastal Ecosystems. South Florida Water Management District, West Palm Beach.
Salomonson, V.V., Barnes, W.L., Maymon, P.W., Montgomery, H.E., Ostrow, H., 1989. MODIS: advanced facility instrument for studies of the Earth as a system. IEEE Transactions on Geoscience and Remote Sensing 27, 145–152.
Schoellhamer, D.H., 1995. Sediment resuspension mechanisms in Old Tampa Bay, Florida. Estuarine Coastal and Shelf Science 40, 603–620.
Shi, J.Z., Luther, M.E., Meyers, S., 2006. Modelling of wind wave-induced bottom processes during the slack water periods in Tampa Bay, Florida. International Journal for Numerical Methods in Fluids 52, 1277–1292.
Shi, W., Wang, M., 2009a. An assessment of the black ocean pixel assumption for MODIS SWIR bands. Remote Sensing of Environment 113, 1587–1597.
Shi, W., Wang, M., 2009b. Satellite observations of flood-driven Mississippi River plume in the spring of 2008. Geophysical Research Letters 36, L07607. http://dx.doi.org/10.1029/2009GL037210.
Shi, W., Wang, M., 2010a. Characterization of global ocean turbidity from moderate resolution imaging spectroradiometer ocean color observations. Journal Geophysical Research 115, C11022. http://dx.doi.org/10.1029/2010JC006160.
Shi, W., Wang, M., 2010b. Satellite observations of the seasonal sediment plume in central East China Sea. Journal of Marine Systems 82, 280–285. http://dx.doi.org/10.1016/j.jmarsys.2010.06.002.
Shi, W., Wang, M. Satellite views of the Bohai Sea, Yellow Sea, and East China Sea. Progress in Oceanography, http://dx.doi.org/10.1016/j.pocean.2012.05.001, in press.
Shi, W., Wang, M., Jiang, L., 2011a. Spring-neap tidal effects on satellite ocean color observations in the Bohai Sea, Yellow Sea, and East China Sea. Journal Geophysical Research 116, C12032. http://dx.doi.org/10.1029/2010JC007234.
Shi, W., Wang, M., Li, X., Pichel, W.G., 2011b. Ocean sand ridge signatures in the Bohai Sea observed by satellite ocean color and synthetic aperture radar measurements. Remote Sensing of Environment 115, 1926–1934. http://dx.doi.org/10.1016/j.rse.2011.03.015.
Siegel, D.A., Wang, M., Maritorena, S., Robinson, W., 2000. Atmospheric correction of satellite ocean color imagery: the black pixel assumption. Applied Optics 39, 3582–3591.
Son, S., Wang, M., 2012. Water properties in Chesapeake Bay from MODIS-aqua measurements. Remote Sensing of Environment 123, 163–174. http://dx.doi.org/10.1016/j.rse.2012.03.009.
Steinman, A.D., Havens, K.E., Aumen, N.G., James, R.T., Jin, K.R., Zhang, J., Rosen, B.H., 1999. Phosphorous in Lake Okeechobee: Sources, Sinks, and Strategies. Lewis Publishing Co., Boca Raton, FL.
Steward, J.S., Virnstein, R.W., Lasi, M.A., Morris, L.J., Miller, J.D., Hall, L.M., Tweedale, W.A., 2006. The impacts of the 2004 hurricanes on hydrology, water quality, and seagrass in the central Indian River Lagoon, Florida. Estuaries and Coasts 29, 954–965.
Stumpf, R.P., Arnone, R.A., Gould, R.W., Martinolich, P.M., Ransibrahmanakul, V., 2003. A Partially Coupled Ocean-atmosphere Model for Retrieval of Water-leaving Radiance from SeaWiFS in Coastal Waters. NASA Goddard Space Flight Center, Greenbelt, Maryland, pp. 51–59.
Switzer, T.S., Winner, B.L., Dunham, N.M., Whittington, J.A., Thomas, M., 2006. Influence of sequential hurricanes on nekton communities in a Southeast Florida estuary: short-term effects in the context of historical variations in freshwater Inflow. Estuaries and Coasts 29, 1011–1018.
Tunberg, B.G., Jones, S., Reed, S., Stephens, M., 2009. Benthic Infaunal Monitoring in St Lucie Estuary and the Southern Indian River Lagoon. South Florida Water Management District, Fort Pierce.
Wan, Y., Labadie, J.W., Konyha, K.D., Conboy, T., 2006. Optimization of frequency distribution of storm-water discharges for coastal ecosystem restoration. Journal of Water Resources Planning and Management 132, 320–329.
Wang, M., 2006. Effects of ocean surface reflectance variation with solar elevation on normalized water-leaving radiance. Applied Optics 45, 4122–4128.
Wang, M., 2007. Remote sensing of the ocean contributions from ultraviolet to near-infrared using the shortwave infrared bands: simulations. Applied Optics 46, 1535–1547.
Wang, M., Shi, W., 2005. Estimation of ocean contribution at the MODIS near-infrared wavelengths along the east coast of the U.S.: two case studies. Geophysical Research Letters 32, L13606. http://dx.doi.org/10.1029/2005GL022917.

Wang, M., Shi, W., 2006. Cloud masking for ocean color data processing in the coastal regions. IEEE Transactions on Geoscience and Remote Sensing 44, 3196–3205.
Wang, M., Shi, W., 2007. The NIR-SWIR combined atmospheric correction approach for MODIS ocean color data processing. Optics Express 15, 15722–15733.
Wang, M., Shi, W., 2008. Satellite observed algae blooms in China's Lake Taihu. Eos, Transactions, American Geophysical Union 89, 201–202. http://dx.doi.org/10.1029/2008EO220001.
Wang, M., Shi, W., Tang, J., 2011. Water property monitoring and assessment for China's inland Lake Taihu from MODIS-Aqua measurements. Remote Sensing of Environment 115, 841–854. http://dx.doi.org/10.1016/j.rse.2010.11.012.
Wang, M., Son, S., Harding Jr., L.W., 2009a. Retrieval of diffuse attenuation coefficient in the Chesapeake Bay and turbid ocean regions for satellite ocean color applications. Journal of Geophysics Research 114, C10011. http://dx.doi.org/10.1029/2009JC005286.
Wang, M., Son, S., Shi, W., 2009b. Evaluation of MODIS SWIR and NIR-SWIR atmospheric correction algorithm using SeaBASS data. Remote Sensing of Environment 113, 635–644.
Wang, M., Tang, J., Shi, W., 2007. MODIS-derived ocean color products along the China east coastal region. Geophysical Research Letters 34, L06611. http://dx.doi.org/10.1029/2006GL028599.